# Phase 2 Project Summary

**Firm: CFD Research Corporation**
**Contract Number: NNX10CB32C**
**Project Title: A Comprehensive CFD Tool for Aerothermal Environment Around Space Vehicles**

**Identification and Significance of Innovation:** (Limit 200 words or 2,000 characters whichever is less)

The goal of this project is to develop a high-fidelity computational tool for accurate prediction of the aerothermal environment around supersonic spacecrafts. This computational tool is based on CFDRC's Unified Flow Solver (UFS) for simulations of rarefied, transitional and continuum flows. In this SBIR project, UFS was enhanced by advanced non-equilibrium chemistry coupled to radiation transport and plasma capabilities. The new models improve the accuracy of simulations of high-speed reacting flows and open a new range of applications. Key Innovations include i) comprehensive physical models for hypersonic flows in the entire range of altitudes and velocities relevant to space vehicles, including multi-scale radiation transport for both optically thick and optically thin regimes and hypersonic plasma models, and ii) smart software with self-aware physics and adaptive numerics using Adaptive Mesh and Algorithm Refinement (AMAR) methodology for automatic mesh generation and dynamic adaptation of computational mesh and physical model for flow conditions.

**Technical Objectives and Work Plan:** (Limit 200 words or 2,000 characters whichever is less)

Technical objectives were: i) Develop a multi-dimensional spectrally resolved multi-scale radiation transport solver applicable for both optically thick and optically thin regimes, ii) Develop a multi-component multi-temperature fluid solver for hypersonic plasmas, and iii) Improve nonequilibrium air plasma chemical reactions models (including excited species and ion-molecule reactions) to model visible/UV emission behind strong shocks. Our work plan consisted of enhancing physical models in Unified Flow Solver with capabilities important for high-enthalpy flow conditions specific to the aerothermal environment around hypersonic vehicles. The new models included: i) an innovative hybrid model of Radiation Transport for weakly ionized non-equilibrium plasma, which combines diffusion approximation ($P_1$) for optically thin parts of the spectrum with Photon Monte Carlo (PMC) model for optically thick parts of the spectrum, ii) new Plasma module in UFS framework using a fluid model for transport of electrons and ions, Poisson equation for the electric field and the electron energy transport for calculation of electron temperature, iii) Coupling radiation transport with gas dynamics and chemistry. We planned to perform testing and verification of the developed code for selected benchmark cases.

**Technical Accomplishments:** (Limit 200 words or 2,000 characters whichever is less)

CFDRC collaborated with the UC Merced (UCM) to develop the Hybrid Radiation Transport Solver with automatic selection of diffusion ($P_1$) or Photon Monte Carlo (PMC) models based on local photon mean free path. An efficient $P_1$ solver was developed for adaptive Cartesian mesh. The PMC solver previously developed by UCM was adapted for efficient photon tracking using fast search algorithms for octree Cartesian mesh. The hybrid $P_1$-PMC solver was integrated with the line-by-line radiative property database generated by UCM. A Multiscale full-spectrum correlated k-distribution model was incorporated for fast and accurate computations of overall radiative fluxes. A framework for incorporating k-distribution based radiative properties for atomic and key molecular species were included using compact high-accuracy databases.

A new Plasma module in UFS framework has been developed. The Plasma module included transport equations for electrons and multiple (positive and negative) ions, Poisson equation for the electric field and the electron energy balance equation for electron temperature. The model was thoroughly tested for simulations of high-pressure corona and streamer discharges as well as low-pressure DC and RF discharges. The gas dynamics module has been improved for hypersonic flow conditions by linking to the CANTERA solver for chemical reactions. Coupling of radiation transport with gas dynamics and chemistry was implemented and demonstrated for atomic lines under conditions of strong radiation trapping.

**NASA Application(s):** (Limit 100 words or 1,000 characters whichever is less)

The computational tool developed in this project will be useful for a multitude of NASA technology development programs. Multiple operational risks may be mitigated, including but not limited to ascent and descent aerothermal effects on Orion Crew Exploration Vehicle (CEV) and Multi Purpose Crew Vehicles (MPCV) components such as the crew capsule and Launch Abort System, plume impact during orbital maneuvering, plume environments during planetary and other landing operations or spacecraft landing near planetary outpost habitat structures. The accurate modeling of aerothermal environments is essential for protecting space vehicles and ensuring crew safety and overall mission success. The code will be used as a design tool for development of new generation reentry vehicles and components of future hypersonic vehicles. The code will be also used for plasma flow control for subsonic and supersonic aerospace applications.

**Non-NASA Commercial Application(s):** (Limit 200 words or 2,000 characters whichever is less)

Technology applications beyond NASA include Ballistic Missile Defense vehicles performing exo-atmospheric missile intercepts, interceptor divert attitude control system (DACS) thruster plume interaction, and the generation of target missile plume signatures. The tool will have wide appeal to rocket engine manufacturers (e.g., ATK, Pratt & Whitney, and Aerojet) and to universities developing rocket engine technology (e.g. Purdue, Penn State, and University of Alabama in Huntsville). Advanced space propulsion systems such as arcjets, ion thrusters, and plasma thrusters must be evaluated for their installed performance and environmental impact. The U.S. Air Force is actively pursuing development of high-speed, long-range, scramjet-powered strike aircraft that will operate at high altitudes presenting complex propulsion airframe interaction challenges. The software may also find numerous commercial and research applications in material processing (hypersonic plasma particle deposition for nanomaterial fabrication) and semiconductor manufacturing.

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